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Note on the use of plaster of paris in flow visualization, and some geological applications

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The pattern of motion on the surface of a model shaped in plaster of paris and immersed in a water stream, can be made visible by reason of the marks caused when small discontinuities in the surface excite local fluctuations of velocity which lead to differential solution of the plaster and to small features of relief. This technique, which has so far been applied in geological studies, is illustrated by reference to motions about a cylinder on a flat plate and over symmetrical skewed steps. Current crescents and sand waves are briefly discussed in the light of these motions.

The methods of fluid mechanics are helpful to geologists interested in the origin and environmental significance of current-formed structures present in sedimentary rocks and in modern sediments. Flow visualization in combination with other techniques has been used to improve understanding of such diverse structures as bed ripples and sand waves in granular sediments, erosional furrows associated with bluff objects on sedimentary surfaces, and structures developed as erosional cavities or grooves of various shapes on flow-boundaries formed of cohesive muds. In connexion with work on ripples and sand waves, a new technique of flow visualization has been developed which may have applications outside the geological field.

The technique is applicable to water-flows and to models that can be shaped in plaster of paris ($CaSO_4$). It relies on the fact that plaster of paris has a very slight solubility in water at room temperature, and reveals the pattern of limiting motion in the flow-boundary. Hence the technique is thought to be similar in its basis to the production of streaks by differential evaporation or sublimation of surface coatings on the boundaries of air streams (Bradshaw 1964, p. 146).

There are two ways of causing streak-like marks on a plaster surface. Both depend on the fact that discrete positive or negative discontinuities in a flow-boundary can, by causing separation, locally excite or amplify fluctuations of velocity in a boundary layer, provided the discontinuities are of a large enough size in relation to the thickness, velocity-gradient, and other properties of the layer. Now the rate of solution of a substance depends, other things being equal, on the rate at which a solvent passes a surface made of that substance. Hence, in the case of a plaster surface exposed to a water stream, more plaster should be dissolved per unit area from places where fluctuations of velocity have been excited or amplified, than from neighbouring places where the velocity field is undisturbed. Given a long enough exposure of the plaster to the flow, the differential solution is found to be expressed on the flow-boundary in terms of small features of relief that are elongated with the stream. The solution effect here described depends solely upon velocity fluctuations arising from separation at small discontinuities, and not upon the local conditions of shear stress which together with the pressure gradient at the surface govern the erosion of insoluble particles. Thus we may map limiting streamlines in the flow boundary by drawing tangents to the streak-like markings.

Tiny bubbles of air or of deliberately introduced gas entrapped in plaster afford one kind of discontinuity that can cause streaks. The bubbles, when once exposed on the flow-boundary through solution of the plaster, act as fixed bluff objects and locally disturb the stream. Close examination shows that a crescentic furrow is generated upstream of each bubble, presumably because of forward separation there, whilst downstream in the region of the wake of the bubble a pattern of long furrows and ridges is produced. The elongation and shape of this structure show unequivocally and permanently the temporal mean path and sign of the flow past the bubble. This method of causing streaks works best when the value of the time-mean velocity close to the bed is large, for the majority of the bubbles are less than 1 mm in diameter.

The second way of producing streaks relies on the fluctuations of velocity excited locally by fixed cavities, 2–3 mm across, in a plaster surface, the cavities being conveniently made by pricking the surface of the model with a hand-held pointed tool. This method is most useful for boundary flows that fluctuate markedly in velocity but which are of small time–mean velocity gradient. Differential solution of the plaster dependent on flow separation at the upstream rim of each cavity causes that cavity to become elongated in the direction of flow into a comet-like mark that flares out and becomes shallower downstream. Again the mean path and sign of the local limiting motion are permanently recorded on the model under study. Referring again to the first way of making streaks, it was found that the spherical cavities when once they had released their bubbles also became reshaped into comet-like marks, in much the same way as the pits made by hand.

We now illustrate the usefulness of this method of flow visualization by reference to three experimental results selected from amongst current studies. The most obvious disadvantage of the method is that the flow-boundary roughness is progressively increased as each experiment proceeds. The presence of streak-marks on a boundary may cause premature transition in a boundary layer, but, if the flow is turbulent throughout, their existence is probably not important. The technique may be valuable in cases in which large fluctuations of the fluid velocity occur, since it gives a temporal mean picture of the flow.

Figure 2 (*a*) (plate 1) shows the flow pattern, recorded by the bubble technique, on the surface of a flat plate on which was mounted a short circular cylinder with axis normal to the plate. As explained by Johnston (1960), Hornung & Joubert (1963) and Sowerby (1965), the boundary layer changes from 'collateral' to 'skewed' as the flow approaches the cylinder. The flow-line divergence associated with this change is strikingly evident in the pattern of streaks. Upstream of the cylinder the flow close to the boundary separates under the influence of the strong positive pressure gradient in the plane of symmetry, and a junction vortex with rapid reverse-flow is set up which curls round the sides of the cylinder. Figure 2(*b*) (plate 1) shows in close-up the pattern of streaks near to the forward singular separation point, estimated to lie at the black dot. The spiral flow of the forward vortex is clearly demonstrated by the orientation of these streaks, and it is an easy matter to estimate the position of the ordinary separation line (broken line in figure).

In order to touch briefly on the geological uses of the technique, we may note that the motion recorded in figure 2 provides a model by which to understand the origin of a sedimentary structure known to geologists as a current crescent. Figure 4 (plate 3) shows a group of current crescents that was photographed from the backwash zone of a modern sand beach, though the same structures could equally well have been illustrated from various sedimentary rocks or from a mud-flat rather than a surface of sand. The two smaller pebbles each lie at the upstream end of a U-shaped furrow that was eroded in the sand as the wave retreated down the beach. The nearly parallel arms of the furrow enclose a narrow ridge of sediment that extends downstream of the pebble a short distance. Presumably, the furrow was eroded by the vigorous action of a spiral junction vortex that was generated upstream of the pebble for the same reason as the vortex demonstrated partly to encircle the cylinder on the plate. The ridge of sediment enclosed by the furrow would appear to represent a deposit formed in the sluggish wake that lay downstream of the pebble. The wake downstream of the cylinder in figure 2(*a*) (plate 1) is clearly evident as a zone of few streak marks, some of which provide evidence of backflow.

The second illustration is of the limiting surface flow, revealed by tool-made pits, upstream and downstream of two negative doubly skewed rigid steps symmetrical about the flow centreline. Figure 3 (plate 2) shows the pattern of comet-like markings on the surface of one such step. A second step of the same general kind is shown in figure 1, in which limiting streamlines in the surface have been mapped by drawing tangents to the comet-like markings. The streamlines are shown as discontinuous in this figure because their behaviour close to the separation and stagnation lines and the corners of the model cannot be determined exactly. A complex pattern of motion is apparent, but we may recognize in each case from the streak marks the bottom-flow in a three-dimensional wake that lies in the region of relatively high pressure between the separation line (continuous line in figure) and an ordinary stagnation line (broken line in figure) on the lower tread of the step. These wakes differ in important respects from the two-dimensional wakes studied by Arie & Rouse (1956), Tani (1957), and Raudkivi (1963), all of whom used discontinuities normal to the flow. In the wakes we illustrate here, there is a component of fluid movement parallel to the wake axis but *away* from the centre-line of the flow. In each case a subsidiary vortex, having a component of movement *toward* the centre-line, nestles in the corner between the riser and lower tread of the step, as illustrated by Tani (1957, fig. 9) for the normal step. The wake and subsidiary vortex form a closed system, in order to satisfy continuity.

This pattern of motion, also, helps geologists to understand phenomena which have been recorded from sedimentary rocks as well as from regions of modern sedimentation. In figure 5 (plate 3) we give a steeply oblique view from upstream into the trough of a sand wave, shaped in groundplan like a wind-formed barkhan dune, but left high and dry in an estuary by the ebbing tide. Down-

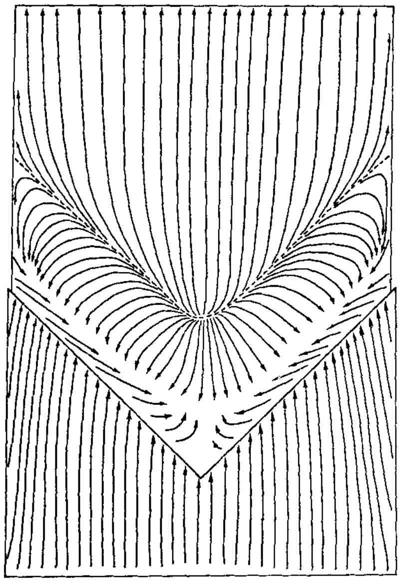

FIGURE 1. Pattern of limiting streamlines sketched in the surface of a doubly-skewed negative step, as inferred from streak marks developed on a plaster model (see figure 3, plate 2, for a similar model but with a smaller angle of skew). Separation line shown as continuous line. Stagnation line shown as broken line. Model is 30 cm wide. Conditions of experiment were very similar to those cited for the model of figure 3 (plate 2).

stream of the curved wave crest is a steep, smooth face down which sand impelled toward the crest has avalanched. In the trough of the wave, below the avalanche face, there are small asymmetrical ripples whose crestlines in groundplan appear as a pattern of 'concentric' ellipses. The complex pattern of sediment movement implied by the main avalanche face, on the one hand, and the small ripples in the wave trough on the other, at once becomes understandable in terms of the motions shown in figure 1 and in figure 3, for the sand wave is similar geometrically to the rigid steps. The outward-directed sediment movement demonstrated by the small ripples suggests that in the trough of the wave there was flow re-attachment along a curved stagnation line and three-dimensional motions similar to those observed on the lower treads of the plaster steps. Separation of the flow with skewing of the boundary layer, must have occurred at the crest of the sand wave, the avalanche face having been consequent on the separation.

Each of the flow-patterns briefly discussed is highly relevant to a geological problem; and flow visualization by means of plaster of paris, in combination with other techniques of experimental fluid mechanics, is helping geologists to explore the significance and mechanisms of generation of sedimentary structures found in rocks and modern deposits. This same technique may be of interest to fluid dynamicists, who may also find the geological problems worthy of study.

I gratefully acknowledge a discussion with Dr D. T. Hopkins, after which came the idea for the particular application of plaster of paris explained in this paper. I am indebted to Prof. J. N. Hunt for helpful advice and suggestions.

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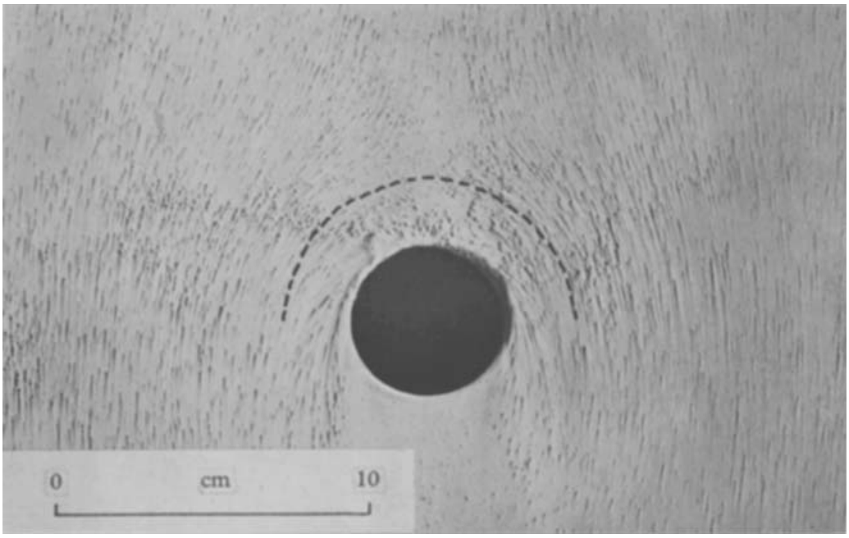
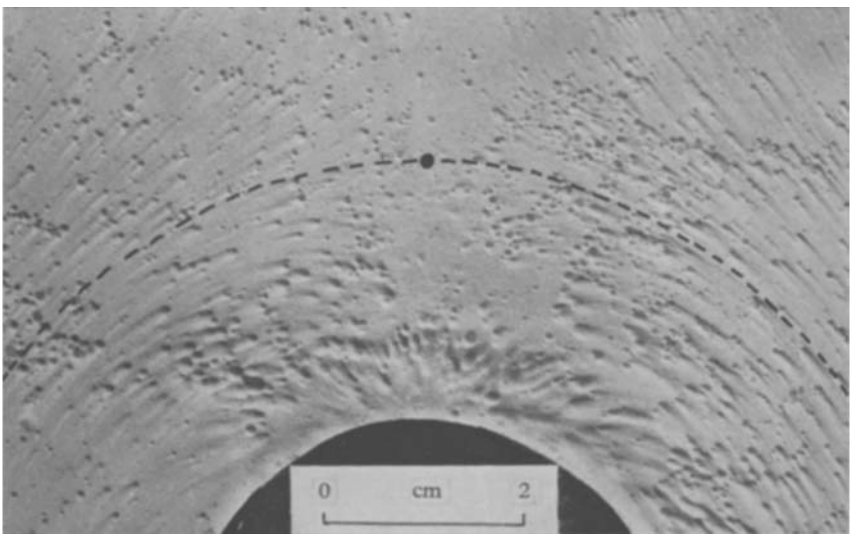


(*a*)



(*b*)

FIGURE 2. (*a*) Motion in surface of flat plate with circular cylinder mounted normal to plate, shown by streaks mainly generated by entrapped bubbles. Flow from top to bottom of figure. Ordinary separation line shown by broken line. Width of channel = 30·7 cm. Mean depth of flow = 10·0 cm. Mean velocity of flow = 45 cm/sec. Reynolds number for cylinder = 11,250. Duration of run = 6 h. (*b*) Motion in surface of flat plate with circular cylinder mounted normal to plate. Detail of figure (*a*) above, to show pattern of streaks in region of separation line. Flow from top to bottom. Note change in sign of streaks across separation line indicating presence of junction vortex forward of cylinder. Flow conditions as given as in (*a*) .

FIGURE 3. Flow-pattern in surface of doubly-skewed negative step as revealed by comet-like markings. Flow from bottom to top of figure. Separation line shown by continuous line. Estimated position of stagnation line shown by broken line. Width of channel = 30·7 cm. Depth of flow measured on upper tread of step = 15·0 cm. Mean velocity of flow measured on upper tread of step = 45 cm/sec. Reynolds number for step (height 2·5 cm) = 10,750. Duration of run = 6 h.

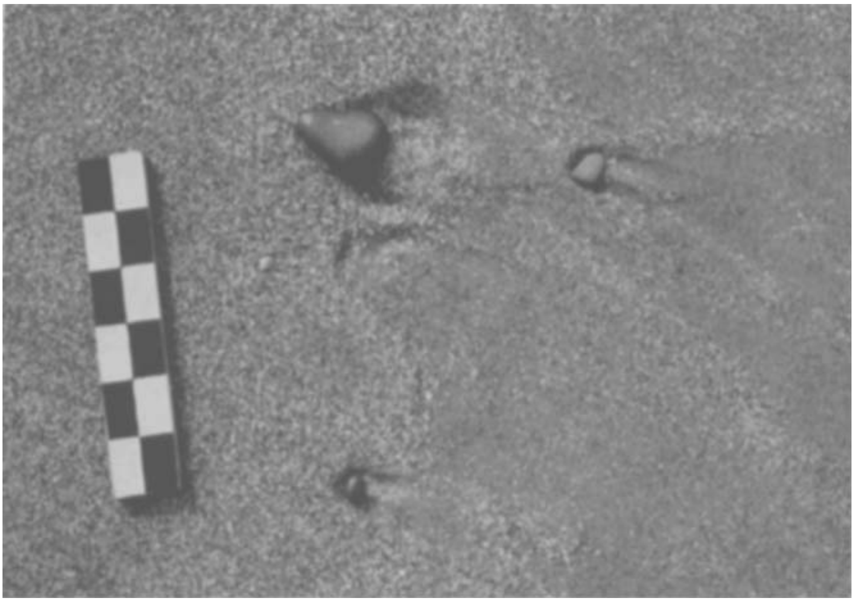


FIGURE 4. Current crescents formed round small pebbles on a sand beach. Scale 15 cm long. The crescents were generated by a wave backwash current that flowed from upper left to lower right. Compare with figure 2 (plate 1).

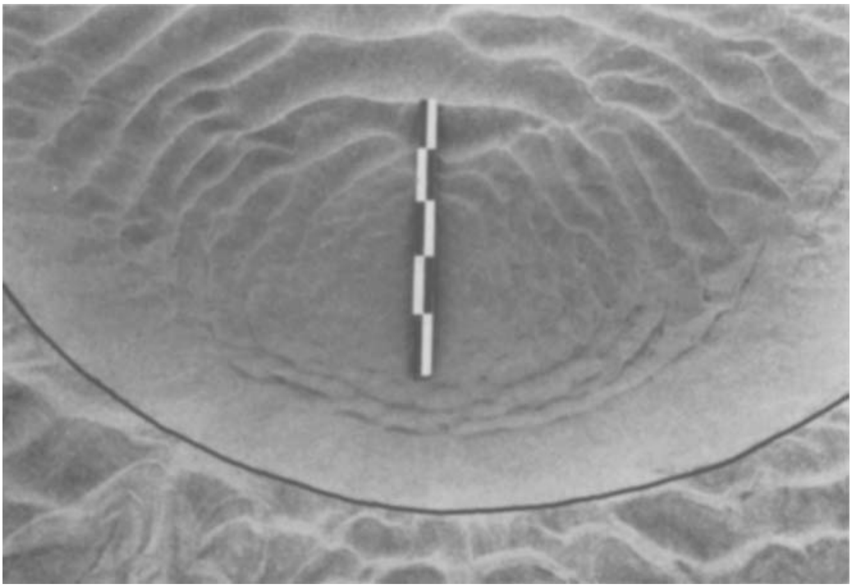


FIGURE 5. Part of crest and trough of an asymmetrical sand wave (or underwater dune) formed in an estuary, as seen obliquely from upstream. The external current flowed from bottom to top, parallel to the scale which is 50 cm long, and separated from the wave at the crest which is marked by a continuous line. Downstream of the crest is a smooth avalanche face of sand about 35 cm in maximum height. The floor of the wave trough shows a concentric pattern of small asymmetrical ripples. The pattern of near-bed flow indicated by these ripples invites comparison with the motions shown in figure 1 and in figure 3 (plate 2).